

DETECTION OF OCEAN REFLECTED GPS SIGNALS: THEORY AND EXPERIMENT

James L. Garrison [†], Stephen J. Katzberg

MS 328 - Spacecraft and Sensors Branch
NASA Langley Research Center, Hampton, VA

[†] (757)864-4441 j.l.garrison@larc.nasa.gov

Charles T. Howell III

Lockheed Martin Engineering & Sciences Co., Hampton, VA

Abstract - A number of advanced applications of the Global Positioning System (GPS) have been proposed which use the signal reflected from a smooth ocean surface. The viability of these concepts hinges upon the ability to acquire and code track the reflected signal for an extended period of time over a variety of sea states. The analytical theory of specularly and diffusely reflected radio frequency radiation from a rough surface is reviewed. Experiments to demonstrate tracking of a reflected signal were performed on three aircraft flights over the Chesapeake Bay and the Eastern Shore of Virginia. The experimental hardware consisted of two off-the-shelf receivers configured so that one received the GPS signal in the conventional manner using a right hand circularly polarized (RHCP) antenna on top of the fuselage and the other could receive the reflected signal using a left hand circularly polarized (LHCP) antenna on the bottom of the fuselage. Three tests were performed on the data to verify that the signals received in the bottom antenna were viewed as sea surface reflections; Pseudorange double differences were compared against predicted geometric range double differences; Characteristics of a signal reflected from a random surface were observed in the carrier to noise ratio; Predicted specular points were plotted which demonstrate reflection only from wet areas. These tests indicated tracking of reflected signals for extended periods of time at altitudes of up to 5500 m and sporadic signal acquisition at higher altitudes. The duration of the continuous signal tracking was limited by the receiver's need to maintain carrier tracking.

INTRODUCTION

The potential for a sea surface reflected GPS signal to interfere with an airborne receiver has been observed by others [1], [2]. All of this previous work has been directed at assessing the effect of the reflected signal as an interference to the normal operation of a GPS receiver. A recent proposal [3], however, seeks to intentionally track the reflected signal for an extended period of time from satellite altitudes as a means of obtaining ionospheric measurements. To follow this theoretical work a series of experiments were performed to determine that this reflected signal can be tracked using conventional off-the-shelf receivers and to develop tests for verifying that the GPS satellites were actually viewed through a sea surface reflection. The first series of tests were ground-based and performed from fixed coastal structures. Next, attempts were made to obtain the same data from aircraft so that these results could be extended to orbital altitudes. This paper presents the results of the aircraft experimentation.

THEORETICAL PREDICTIONS

The ability of a receiver to track a reflected GPS signal is dependent upon two basic factors, the power in the reflected signal and how the code-correlation process performs on a reflected signal.

At the GPS broadcast frequency of 1575 MHz the Rayleigh criterion predicts that specular reflection would only occur with rare conditions of exceptionally calm seas. Under specular conditions the reflected signal would be similar to the direct signal, differing only in polarization and small losses from the reflecting surface and the additional path length.

The effect of scattering under the common diffuse conditions is a more complex problem. Consider the power returned from the surface reflections which lie

within one code chip of the specular reflection. (The specular point, of course, represents the shortest path length) The reflected power density can be expressed as the product of the direct power, a space loss term, the scattering cross section at the surface and the scattering area.

$$P_R = P_D \left(\frac{1}{4\pi r^2} \right) \sigma_o A_R \quad (1)$$

A model for a random, normally distributed reflecting surface was derived in [4]. That model gave the scattering cross section as

$$\sigma_o(\beta) = \cot^2(\beta_o) \exp \left(-\frac{\tan^2 \beta}{\tan^2 \beta_o} \right) \quad (2)$$

In (2) β is an angle describing the scattering geometry defined as the angle between the surface normal and the bisector of the incident and reflected rays. (see figure 1.) β_o is a constant describing the surface rough-

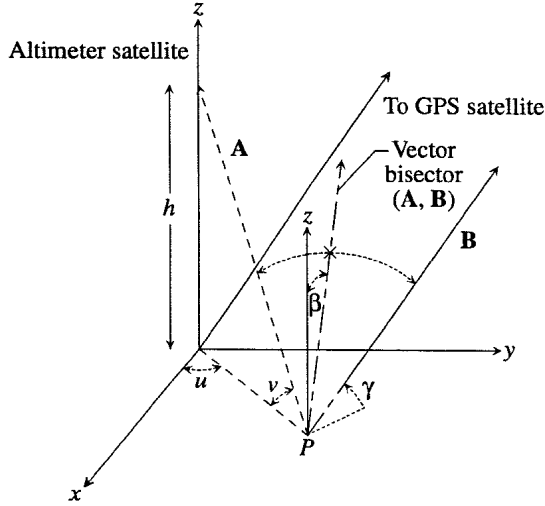


Figure 1: Scattering Geometry Defining Bisector Angle β

ness and is defined as

$$\beta_o \equiv \tan^{-1} \frac{2\sigma}{T} \quad (3)$$

where σ is the standard deviation of the height distribution and T is the correlation length. The quantity $\tan \beta_o$ represents the root mean square value of the slope of irregularities on the reflecting surface.

The region bounded by $\beta = \beta_o$ is defined as the “glistening surface” and $\sigma_o(\beta)$ rapidly decreases in value for $\beta > \beta_o$. Furthermore, within the glistening surface $\sigma_o \approx \cot^2 \beta_o$. This allows the following approximation to the scattering cross section to be made.

$$\sigma_o(\beta) = \begin{cases} \cot^2 \beta_o & \beta \leq \beta_o \\ 0 & \beta > \beta_o \end{cases} \quad (4)$$

The surface area corresponding to a fixed delay $c\tau$ is an ellipse centered at the specular point. The area of this ellipse can be shown to be

$$A_R = \frac{2\pi h c \tau}{\sin^2 \gamma} \quad (5)$$

in which γ is the grazing angle. The path length from the specular point is $r = h / \sin \gamma$. Substituting this, along with (4) and (5) into (1) results in the expression

$$P_R = P_D \frac{c\tau}{2h} \cot^2 \beta_o \quad (6)$$

stating that the received power density is inversely proportional to the altitude. This assumes that the locus of points with time delay less than τ lies within the glistening surface.

Theory of the effect of the reflected signal on the code-correlation process is given in [3]. Essentially the requirement is made that the code-correlation process occurs on a much faster time scale than the scattering geometry changes. When this condition, which is not unreasonable, is made then the time averaging involved in the correlator takes a smoothed “snap shot” of the instantaneous sea state. The returned signal would be the result of a distribution of time delays, the variation of which would depend upon the extent of the glistening surface.

EXPERIMENT DESCRIPTION

A series of three flights were made using the Langley Research Center Boeing 737 on August 6, 8 and 27, 1996. Two receivers [5], one connected to conventional Right-Hand Circularly Polarized (RHCP) antenna on the roof of the aircraft and the other connected to a Left-Hand Circularly Polarized (LHCP) antenna on the bottom of the fuselage were used. Both receivers were programmed to track any satellites visible and record the following: code pseudorange, carrier pseudorange, carrier to noise ratio (C/N_o), and Pseudorange Noise (PRN) number. Additionally, the zenith receiver was operated as a conventional navigation receiver, recording the aircraft flight path for later post-processing with differential corrections. The visibility mask angle was set to 0 deg on the nadir antenna and 7 deg on the zenith antenna.

DATA REDUCTION

For every satellite that was acquired in the nadir receiver three independent tests were made to determine that this signal was received through a reflection of the sea surface or a wet ground area. These tests were; pseudorange double differences, examination of

the carrier to noise ratio (C/N_o), and plotting the location of specular reflection points.

The aircraft flight path was obtained by post-processing the data from the zenith receiver with differential corrections provided by two reference stations, one at the Langley Research Center and the other at the Wallops Is. Flight Facility. The precise GPS ephemerides provided by the National Geodetic Survey (NGS) was used to obtain the positions of the GPS satellites in WGS-84 coordinates. The GPS satellite positions were interpolated to each time that a measurement was made using the Lagrange method described in [6].

1.) Double Differences

The geometric path length of a reflected signal broadcast from the i^{TH} GPS satellite, reflected from a specular point with coordinates (ϕ_S, λ_S) , and received in the LHCP antenna located at (X_L, Y_L, Z_L) is given by

$$\rho_{L_i}(\phi_S, \lambda_S) = \dots \quad (7)$$

$$\frac{\sqrt{(X_L - X_S)^2 + (Y_L - Y_S)^2 + (Z_L - Z_S)^2} + \dots}{\sqrt{(X_{GPS_i} - X_S)^2 + (Y_{GPS_i} - Y_S)^2 + (Z_{GPS_i} - Z_S)^2}}$$

$$X_S = \frac{a^2 \cos \phi_S \cos \lambda_S}{\sqrt{a^2 \cos^2 \phi_S + b^2 \sin^2 \phi_S}} \quad (8)$$

$$Y_S = \frac{a^2 \cos \phi_S \sin \lambda_S}{\sqrt{a^2 \cos^2 \phi_S + b^2 \sin^2 \phi_S}} \quad (9)$$

$$Z_S = \frac{b^2 \sin \phi_S}{\sqrt{a^2 \cos^2 \phi_S + b^2 \sin^2 \phi_S}} \quad (10)$$

A 4 m vertical separation between the LHCP and RHCP antenna was assumed and attitude motion of the aircraft was not accounted for. Reflection directly off of the WGS-84 ellipsoid was assumed. In reality the local sea could deviate from this surface on the order of 30 m. Neither of these two assumptions would effect the capability of the tests to identify a reflected signal, with path length double differences on the order of kilometers from the direct signal with double differences at most equal to the 4 m antenna separation.

The location of the specular point on the surface of an ellipsoidal Earth was found by numerically minimizing ρ_{L_i} .

Geometric double differences were then computed from the ρ_{L_i} above and the direct path length (ρ_{R_i}). These should be equal to the experimental pseudorange double difference ($c\delta t$) for any two satellites, A and B .

$$\Delta\Delta = c[(\delta t_{L_A} - \delta t_{L_B}) - (\delta t_{R_A} - \delta t_{R_B})] \quad (11)$$

2.) Carrier to Noise Ratio

The reflected signal would have a very similar structure to the direct signal with two important differences. The polarization would be reversed (RHCP to LHCP) and the instantaneous signal strength would vary randomly depending upon the sea state. If the satellite has a given Carrier to Noise Ratio (C/N_o) when tracked normally in the zenith receiver through an RHCP antenna then the C/N_o for the same satellite when tracked in the nadir antenna through an LHCP antenna should reach values almost as large. It should show a much larger variation, however, because of the time-dependent variation of the sea surface. If, on the other hand, a direct signal was tracked in the nadir antenna through the LHCP antenna then the signal strength would be decreased due to the reversed polarization. The signal variation in this case would be small because it would not suffer from the introduction of noise from varying sea state.

3.) Mapping of Specular Points

The third independent test performed on these data was to plot the location of this specular point ($\phi_{L_i}, \lambda_{L_i}$ above) onto a map illustrating land, sea, and marsh boundaries. For all times, except when the aircraft was at very low altitudes, the specular points should lie only on wet areas.

RESULTS

Figure 2 plots the altitude profile for a segment of the August 8, 1996 flight in which the aircraft climbs to 5500 meters and circles. In figure 3, the predicted geo-

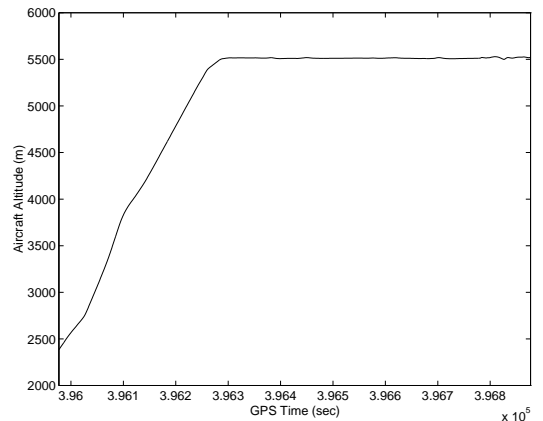


Figure 2: Altitude Profile: August 8, 1996 Flight

metric double differences computed following (7) above are plotted on top of the measured double difference for satellites PRN 4 and PRN 5 using (11). This shows

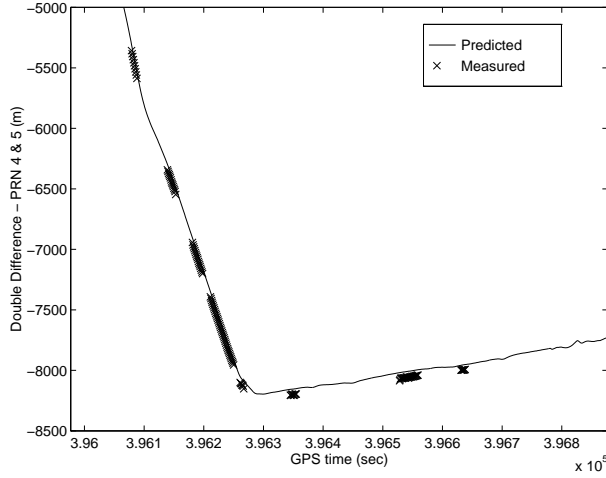


Figure 3: Double Difference PRN 4 and PRN 5: August 8, 1996 Flight

that these double differences agree. Figure 4 plots the

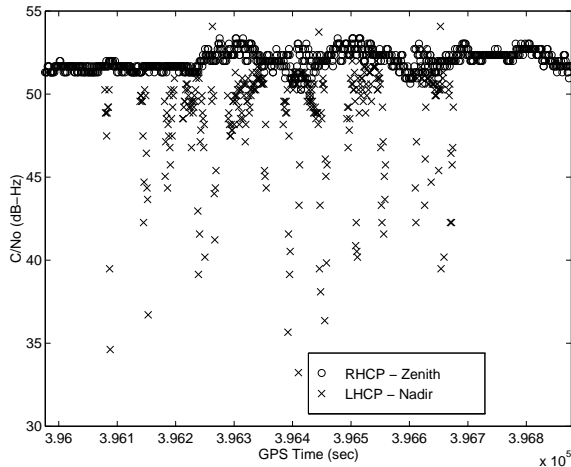


Figure 4: Carrier to Noise Ratio for RRN 4: August 8, 1996 Flight

carrier to noise ratio (C/N_o) for PRN 4 obtained in the zenith receiver and in the nadir receiver for comparison. This plot exhibits the characteristics described above in that the Zenith receiver maintains lock on the signal with a C/N_o around 52 dB-Hz whereas the C/N_o of the nadir antenna varies from 30 dB-Hz to 54 dB-Hz with a large number of points in the 48 to 52 range. The flight path of this section of the August 8 flight is shown in figure 5 Plotted over top of this map is the locations of the specular reflection points for all instances in which of a satellite was tracked in the nadir receiver. As this figure demonstrates, the reflections occur almost exclusively over wet areas.

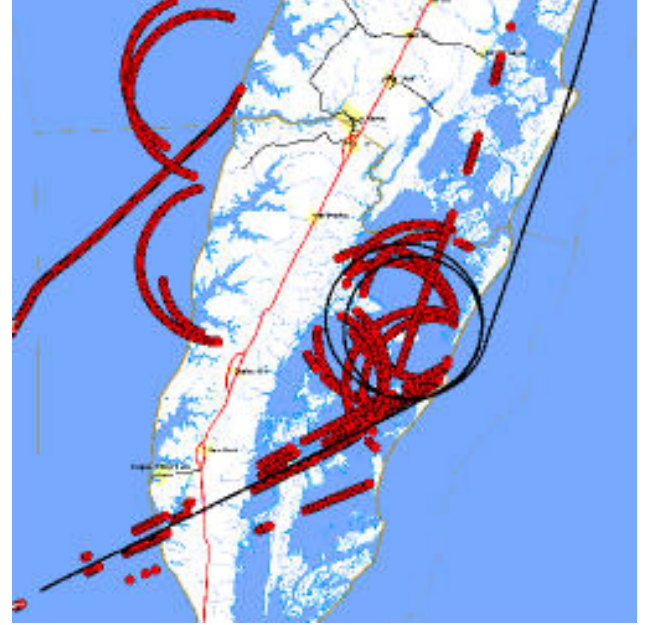


Figure 5: Specular Points (Converted to NAD-27 Datum): August 8, 1996 Flight

An excerpt of the data from the August 27, 1996 flight is plotted in figures 6 through 8. The altitude, as shown in figure 6 is 300 meters. Figure 7 plots

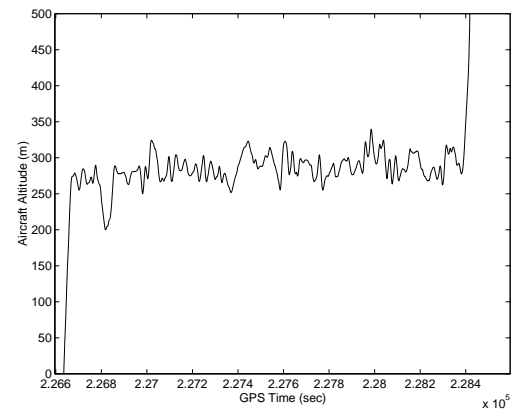


Figure 6: Altitude Profile: August 27, 1996 Flight

the double differences between satellites PRN 5 and PRN 18 for the flight. In figure 8, the flight path is plotted over top of the mapping of the specular points. This figure again confirms that the reflections occur predominantly over wet areas.

Examination of the complete set of data revealed that a carrier lock was obtained for each instance of tracking a satellite in the nadir antenna. It was confirmed that a carrier lock is required for the receiver to output data [7]. It is difficult to get a carrier lock

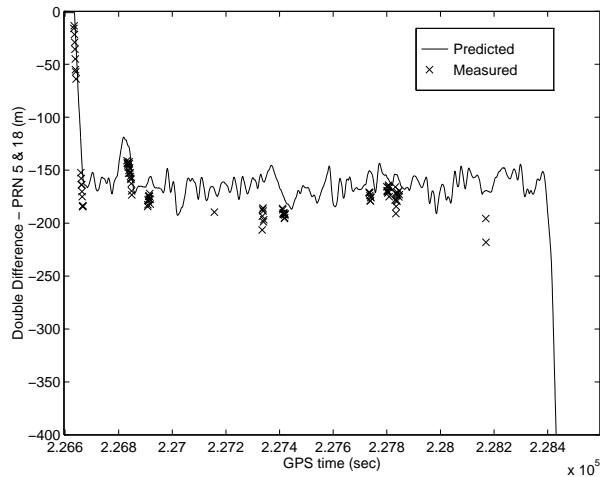


Figure 7: Double Difference PRN 5 and PRN 18: August 27, 1996 Flight

on any reflected signal from a rough surface so this indicates that the data which was obtained was only suggestive of what is possible with more specialized code tracking receiver hardware.

CONCLUSION

The experimental data presented in this paper shows that the reflected signal was tracked by a conventional GPS receiver using a left hand circularly polarized (LHCP) antenna. The extent for which the receiver maintained tracking of the reflected signal was limited by the need to obtain a carrier lock. Furthermore, the dimensions of the glistening surface at satellite altitudes may encompass several code chips and consequently the code-correlation process will be presented with a distribution of time delays from which the specular delay must be obtained. In order to more reliably track the sea surface reflected GPS signal over a longer period of time and to extract additional information from this signal, it is apparent that a specialized receiver must be developed or adapted from existing configurable GPS development systems.

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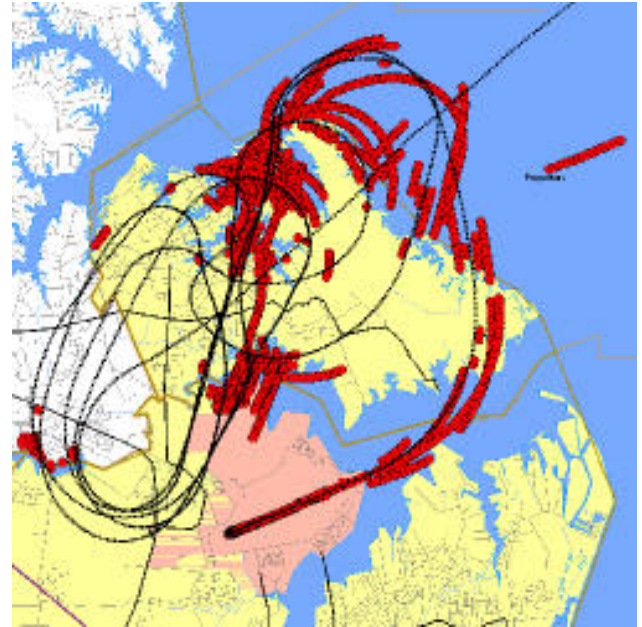


Figure 8: Specular Points (Converted to NAD-27 Datum): August 27, 1996 Flight

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